MAGNETIC ACTIVITY OF THE COOL COMPANION IN SYMBIOTIC SYSTEMS

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ABSTRACT

I argue that cool giant companions in most symbiotic binary systems possess magnetic activity on a much higher level than isolated, or in wide binary systems, cool giants. Based on the behavior of main sequence stars, I assume that magnetic activity and X-ray luminosity increase with rotation velocity. I then show that the cool companions in symbiotic systems are likely to rotate much faster than isolated, or in wide binary systems, cool giants. The magnetic activity of the cool giant may be observed as a global axisymmetrical mass loss geometry from the cool giant (before the hot companion influences the outflow), a stochastic mass loss process, i.e., variation of mass loss rate with time and location on the giant's surface, and in relatively strong X-ray emission. The variation in the mass loss process from the cool giant may cause variation in the properties of jets blown by the hot compact companion. I conclude that symbiotic systems should be high-priority X-ray targets.

Subject headings: binaries: symbiotic – circumstellar matter – stars: AGB – stars: magnetic fields

1. INTRODUCTION

The level and the nature of the magnetic activity in red giant branch (RGB) and asymptotic giant branch (AGB) stars is poorly known and understood. Indications of magnetic activity come from polarized maser emission and X-ray emission from a number of AGB stars. Polarized SiO maser emission is observed close, typically less than a few stellar radii, to some evolved stars (e.g. Kemball & Diamond 1997), whereas polarized OH maser emission is observed at $\sim 10^{15} - 10^{16}$ cm from the star (e.g., Zijlstra et al. 1989; Szymczak, Cohen, & Richards 1999; Miranda et al. 2001). X-ray emission found in several evolved stars (e.g., Hünsch et al. 1998; Schröder, Hünsch & Schmitt 1998; Hünsch 2001) may indicate the presence of a hot corona that results from magnetic activity.

The dynamo in evolved stars, e.g., AGB stars, is different in many respects from the dynamo mechanism in the Sun. The main difference is the ratio between the rotation period, $P_{\rm rot} = 2\pi/\omega$, and the convective overturn time τ_c (Soker & Zoabi 2002). This is defined as the Rossby number $\mathrm{Ro} \equiv (\omega\tau_c)^{-1}$. In the sun and other magnetically active main sequence stars, $Ro < 1$, whereas in evolved stars $Ro \gg 1$. In cool giant stars, therefore, the amplification is most likely via a turbulent dynamo, i.e., an $\alpha\alpha$ dynamo, but where the rotation plays a positive role (Soker 2000b; Soker & Zoabi 2002). This mechanism is termed $\alpha^2\omega$ dynamo. If indeed rotation plays a significant role in the amplification of the magnetic field in cool giant stars, then systems where these stars rotate fast would be expected to be more active. Such systems are symbiotic stars (SSs), which are binary systems composed of a mass losing evolved star, basically an RGB or an AGB star, and an accreting compact star, in most cases a white dwarf (WD), and in the minority of the systems a close main sequence (MS) star (e.g., Belczynski, et al. 2000).

In §2 I show that the cool companion in symbiotic systems are likely to rotate much faster than single cool giant stars, hence they are prime candidates for possessing (relatively) strong magnetic activity. The presence of magnetic fields coronae in SSs were proposed in the past, e.g., to account for UV emission (Stencel & Sahade 1980). A thorough review of binary evolution and interaction in symbiotic stars is given by Iben & Tutukov (1996). I will only concentrate on the expected rotation speed of AGB cool companions in these systems, and the expected magnetic activity. In §3 I discuss the manifestation of the expected magnetic activity, and in §4 I present my main conclusions, and propose some future observations.

2. SPINNING-UP THE COOL COMPANION

2.1. Accretion during the main sequence phase

In this subsection I consider SSs with a WD hot companion. I show that the presently cool giant companion was spun-up when it was an MS star and the presently WD was an AGB star. In most SSs the accretion rate into the WD companion is $\dot{M}_{\rm acc} > 10^{-9} M_\odot$ yr^{-1}, the orbital period is $P_{\rm orb} < 10^4$ day, the mass loss rate (defined positively) from the cool companion is $\dot{M}_w < 10^{-5} M_\odot$ yr, and the WD mass is $M_{WD} \gtrsim 0.6 M_\odot$. The parameters of most systems, in particular the mass of the WD companion, indicate that the progenitor of the WD companions was relatively massive $M_p \gtrsim 3 M_\odot$. Such stars lose $M_l \simeq 1 - 2 M_\odot$ as a slow wind during their AGB phase. Some fraction of this mass is accreted by the MS progenitor of the presently giant star. To find the accreted angular momentum by the MS progenitor of the present cool giant, I use the Bondi-Hoyle mass accretion rate, and the angular momentum entering the Bondi-Hoyle accretion cylinder (Wang 1981), i.e., having impact parameter $b < R_a = 2GM_g/v_r^2$, where R_a is the accretion radius, M_g is the mass of the accreting star, and v_r the relative velocity of the star and the wind. The accreted angular momentum onto the MS progenitor of the present giant is given by (for $R_a < a$; see relevant equations and more references in Soker 2001)

$$J_{\rm acc} = \frac{\eta}{4} \left(\frac{R_a}{a} \right)^4 \frac{M_l}{\mu} [G(M_g + M_p) a \mu^2]^{1/2}, \tag{1}$$

where $\mu = M_g M_p/(M_g + M_p)$ is the reduced mass of the binary system, M_p is the mass of the WD's progenitor, η is the ratio of the accreted angular momentum to that entering the Bondi-Hoyle accretion cylinder, and a is the orbital separation (for simplicity a circular orbit is assumed). The last term in equation (1) (the $[]^{1/2}$ term) is the total orbital angular momentum of the binary system. I took the wind velocity v_w to be equal to the relative velocity $v_r = (v_w^2 + v_o)^{1/2}$, where v_o is the orbital velocity of the accreting star relative to the mass losing star. This is justified for the parameters used here and the other uncertainties, e.g., in the value of η. Scaling the different variables with typical values, I find the accreted angular momentum to be

$$J_{\rm acc} \simeq 10 J_\odot \left(\frac{\eta}{0.2} \right) \left(\frac{M_g + M_p}{4 M_\odot} \right)^{1/2} \left(\frac{M_g}{1.0 M_\odot} \right)^4 \left(\frac{M_l}{1 M R_\odot} \right) \left(\frac{a}{50 \text{ AU}} \right)^{-7/2} \left(\frac{v_r}{15 \text{ km s}^{-1}} \right)^{-8}, \tag{2}$$

where $J_\odot = 1.7 \times 10^{48}$ g cm^2 s^{-1} is the present angular momentum of the Sun. Stars more massive than the sun rotate faster, up to 100 times faster, but accrete much more angular momentum, e.g., by a factor of ~ 100 for $M_g = 3 M_\odot$. Of course, the MS can't rotate faster than the break-up velocity. The conclusion from the last equation is that the present giant in most SSs reach the RGB and AGB with typical angular momentum, hence angular velocity, much larger than isolated stars do.

As an example I consider Mira (o Ceti) a non-SS binary system with an AGB star and a WD in a projected orbital separation of ~ 70 AU (Karovska et al. 1997). The true orbital separation is larger, but it was smaller before mass was lost by the two components. Taking therefore $a = 70$ AU in equation (2) with all other parameters held the same, gives $J_{\rm acc} \simeq 3 J_\odot$. If, on the other hand, the slow wind speed were lower, as is quite plausible for a large AGB star, as the progenitor of the WD was, say $v_w = 10$ km s^{-1}, then $J_{\rm acc} \simeq 75 J_\odot$. I suggest, therefore, that Mira has reached the AGB with an angular momentum larger than typical isolated AGB stars do, despite the orbital separation that is too large to allow substantial tidal spin-up (see next subsection). Such an extra spin may enhance magnetic activity (see §3), which may lead to a stochastic mass loss process (§3.2), which may explain Mira's asymmetrical shape observed by Karovska et al. (1997) and Marengo et al. (2001).

2.2. Tidal interaction

The hot companion spins-up the cool giant companion via tidal interaction, whereas mass loss from the giant spins it down. I use the equilibrium tidal interaction for giants (Zahn 1977; 1989; Verbunt & Phinney 1995) with time scales from Soker (1998). The circularization time of the orbit is given by

$$\tau_{\rm circ} = 1.2 \times 10^8 \frac{1}{f_s} \left(\frac{L_g}{2000 L_\odot}\right)^{-1/3} \left(\frac{R_g}{200 R_\odot}\right)^{2/3} \left(\frac{M_{\rm env}}{M_g}\right)^{-1} \left(\frac{M_{\rm env}}{M_\odot}\right)^{1/3} \times \left(\frac{M_2}{M_g}\right)^{-1} \left(1+\frac{M_2}{M_g}\right)^{-1} \left(\frac{a}{10 R_g}\right)^{8} {\rm yr}, \tag{3}$$

where L_g, R_g and M_g are the luminosity, radius, and total mass of the giant star, $M_{\rm env}$ is the giant's envelope mass, M_2 is the mass of companion that exerts the tide, a is the semi-major axis, and $f_s(e)$ is a steeply increasing function of eccentricity e (Hut 1982) with $f_s(0) \simeq 1$. The transferring rate of orbital angular momentum to giant spin is

$$\dot{J}_{\rm orb} \simeq \frac{\dot{a}}{2a} J_{\rm orb} \simeq \frac{J_{\rm orb}}{\tau_{\rm cir}}, \tag{4}$$

where $J_{\rm orb}$ is the total orbital angular momentum of the two stars, and dot stands for time derivative. The expression is accurate for a circular orbit; for eccentric orbits there is a factor of correction (see Hut 1982 for the dependence of the different factors on eccentricity). I don't consider this factor here, because the mass loss process, if it depends on the orbital phase, may lead to a change in eccentricity, which is not considered here either. The giant slows-down because of angular momentum loss via mass loss, at a rate given by

$$\dot{J}_w = \beta R_g^2 \omega \dot{M}_w, \tag{5}$$

where ω is the giant's angular velocity, $\dot{M}_w$ is the mass loss rate in the wind, and β is a parameter that depends on the mass loss geometry; $\beta = 2/3$ for spherical mass loss and $\beta = 1$ for equatorial mass loss. Both J_w and M_w are defined positively. In systems in which the evolution time is less than the circularization time, the angular velocity of the giant is given by equating the rate in equation (4) to that in equation (5), where I neglect the nagular momentum of the spining giant's envelope. This gives

$$\frac{\omega}{\omega_{\rm Kep}} \simeq \left(\frac{M_g + M_2}{M_g}\right)^{1/2} \left(\frac{a}{R_g}\right)^{1/2} \frac{\mu}{\dot{M}_w} \frac{(1-e^2)^{1/2}}{\tau_{\rm cir}} \frac{1}{\beta}, \tag{6}$$

where $\omega_{\rm Kep}$ is the Keplerian angular velocity on the equator of the giant, and $\mu = M_g M_2/(M_g + M_2)$ is the reduced mass of the binary system. Substituting typical values and omitting terms of weak dependence on several factors in equation (3) (in any case, as indicated above, $\tau_{\rm cir}$ serves as approximation for the rate of angular momentum transfer in eccentric orbits) and taking $M_2 \simeq M_g \simeq M_\odot$, this ratio is

$$\frac{\omega}{\omega_{\rm Kep}} \simeq 0.03 f(e) \left(\frac{M_{\rm env}}{M_g}\right) \left(\frac{M_{\rm env}}{M_\odot}\right)^{-1/3} \left(\frac{a}{10R_g}\right)^{-15/2} \left(\frac{\dot M_w}{10^{-6} M_\odot ~{\rm yr}^{-1}}\right)^{-1}, \tag{7}$$

where $f(e) \equiv f_s(e)(1-e^2)^{1/2}$ is a steeply increasing function of e, with $f(0) \simeq 1$. I emphasize again that this relation holds only if the time spent by the mass losing star in the giant phase is shorter than the synchronization time $\tau_{\rm syn}$, only for mass loss via a wind (not for a Roche lobe overflow), and only if it gives $\omega < \omega_o$, where ω_o is the orbital angular velocity. The synchronization time is related to the circularization time by the expression $\tau_{\rm syn} \simeq (1 + M_2/M_1)(M_2/M_1)^{-1}(I_g/M_g R_g^2)(R/a)^2 \tau_{\rm cir}$ (accurate for $e = 0$), where I_g is the giant's moment of inertia. Using the typical values as in equation (3), I find equation (7) to hold for $3R_g \lesssim a \lesssim 20R_g$, for a circular orbit; the separation can be larger for eccentric orbits.

Crudely, equation (7) indicates that in all symbiotic systems with orbital period of $P_{\rm orb} \lesssim 100$ yr, with larger periods for larger eccentricity, tidal interaction overcomes angular momentum loss, and the systems are synchronized, or close to being so. For systems with $a \gtrsim 5R_g$, the situation is reversed during the superwind phase at the termination of the AGB, when the mass loss rate can be as large as $\sim 10^{-4} M_\odot ~{\rm yr}^{-1}$, and the giant envelope loses synchronization and slows down. This is more relevant to the formation of some bipolar planetary nebulae than to SSs.

2.3. Backflowing material

The basic process here is that the hot companion prevents, directly or indirectly, part of the mass blown by the giant companion to acquire the escape velocity from the binary system. That fraction of mass may acquire orbital angular momentum, and if it is accreted back by the giant, it spins-up the giant's envelope. This process should be worked out in detail via numerical simulations, e.g., similar to those of Mastrodemos & Morris (1999), but with more processes included, e.g., locally enhanced mass loss rate. The conditions for a backflow to occur were examined in an earlier paper (Soker 2001). I found there that for a significant backflow to occur, there should be a slow dense flow, such that the relation between the total mass in the slow flow, M_i, and the solid angle it covers Ω, is given by $M_i/(\Omega/4\pi) \gtrsim 0.1 M_\odot$. The requirement for both high mass loss rate per unit solid angle and a very slow wind, such that it can be decelerated and flow back, probably requires close binary interaction. This process, therefore, requires that the companion be close and already some spin-up of the giant's envelope have occurred. Large magnetic cool spots (see next section) may then lead to a very slow and a high mass loss rate above these spots. Because the escape velocity from the binary system is larger than that from the mass losing star, some of this material may be accreted back by the giant (or the companion). The gravitational interaction with the binary system may transfer some orbital angular momentum to the backflowing mass, e.g., in the accretion column formed behind the companion. The backflowing material, then, may possess large specific angular momentum and spin-up the giant.

I suggest this process to account for the rotation of the SiO maser shell in R Aquarii (Hollis et al. 2001). Hollis et al. (2001) argue for a rotational period range of 8-34 yr, at a radius of $\sim 1-2R_g$, where $R_g = 1.8$ AU is the giant's radius. The orbital period of the R Aquarii binary system is ~ 44 yr, with a semimajor axis of ~ 17 AU, and an eccentricity of ~ 0.8 (Hollis et al. 2001). The tidal synchronization time is very short for this system, hence, the angular velocity of the spinning giant should have been ~ 44 yr. Any mass lost by the giant should have a longer rotation period, and not as short as $\sim 8-34$ yr. The fast rotating maser spots are formed by backflowing material, as is indeed observed by Boboltz, Diamond, & Kamball (1997). In particular, a high mass loss rate is expected during the periastron passage. A substantially enhanced mass loss rate during periastron passage may account for the high eccentricity of the system, despite the short circularization time (Soker 2000a). The backflowing mass, which is the source of the SiO maser, further spins-up the giant's envelope. Also, because of the fast rotation of the backflowing gas, there will be a shear as it reaches the stellar surface. Such a shear may further amplify the magnetic field near the equator (Soker 2000b).

3. MAGNETIC ACTIVITY

The three processes discussed in the previous section show that the giant companion in many SSs is likely to rotate much faster than isolated, or in wide binary systems, RGB and AGB stars. In the present section I discuss plausible implications of this (relatively) fast rotation to the magnetic activity of these cool giants.

3.1. Global mass loss geometry

A strong magnetic activity may influence the mass loss geometry, e.g., cause a higher or lower mass loss rate in the equatorial plane, and/or cause semi-periodic variation via a solar-like magnetic activity cycle. The magnetic field may influence the mass loss process via dynamical effects, i.e., the magnetic force due to pressure gradient and/or tension directly influences the outflowing mass (e.g., Chevalier & Luo 1994; Pascoli 1997; Matt et al. 2000; Blackman et al. 2001; García-Segura et al. 1999; García-Segura, López, & Franco 2001; Gardiner & Frank 2001). As far as the shaping of circumstellar gas is concerned, my view is (Soker & Zoabi 2002; Soker 2002) that the global shaping mechanisms are based on direct influence of a companion (e.g., Mastrodemos & Morris 1999) or indirect effects of the magnetic field but not on direct dynamical effects of the giant's magnetic field. I find this to be the case in the SS system R Aquarii, from the following consideration. In the sun the magnetic activity determines the mass loss rate. Indeed, the average solar X-ray luminosity resulting from the magnetic activity is within an order of magnitude of the kinetic energy carried by the solar wind. In the SS R Aquarii, the X-ray luminosity of the central source is much lower than the rate of kinetic energy carried by the giant's wind. From the results of Kellogg, Pedelty, & Lyon (2001), the central X-ray luminosity is $L_x \sim 4 \times 10^{28}$ erg s^{-1}. The rate of wind's kinetic energy is $L_w = 3 \times 10^{30}$ erg s$^{-1}(\dot{\rm M}_{\rm w}/10^{-7}{\rm M}_\odot$ yr$^{-1})({\rm v_w}/10$ km s$^{-1})^2$, where v_w is the wind speed. The mass loss rate from R Aquarii is somewhat smaller than the scaling above (see data summarized by Iben & Tutukov 1996), but the outflow speed is larger (Hollis et al. 1999). The low ratio of $L_x/L_w < 0.01$ in R Aquarii hints that the mass loss process from the cool giant is not determined directly by magnetic activity. Indirect effects of the magnetic field are very likely, though. In §3.3 I speculate that some of the central X-emission of R Aquarii may result from magnetic activity on the giant's surface.

An indirect effect can be the formation of magnetic cool spots, above which dust formation, hence mass loss rate, is enhanced (Soker 2000b and references therein). Globally, the magnetic energy is much below that carried by the wind, although in local spots the magnetic field can be strong. Magnetic cool spots can be concentrated in the equatorial plane as in the sun, leading to higher mass loss rate in the equatorial plane. It is also possible, probably in rapidly rotating stars, that the spots are concentrated in the polar regions, as in rapidly rotating MS stars (e.g., Schrijver & Title 2001). To conclude, relatively strong magnetic activity may lead to axially symmetric mass loss process.

If a magnetic activity cycle exists, then the mass loss rate may be semi-periodic (Soker 2000b). This means that a mass loss rate presently observed in a specific system may not represent the average mass loss rate.

3.2. Stochastic mass loss

One manifestation of magnetic cool spots is locally enhanced mass loss rate, i.e., in particular directions the mass loss rate is higher for a short time. A similar effect can be caused by spots formed by large convective elements (Schwarzschild 1975). This means, as mentioned above, that the surface of the cool giant can be asymmetric. Another implication is a stochastic mass loss rate in the direction of the hot companion, hence the accretion rate and geometry onto the hot companion may vary during short periods, i.e., weeks to years (much shorter than a possible magnetic cycle). This stochastic accretion process may have the following observable manifestations. (1) Impulsive jets: A high mass flux in a specific direction toward the companion, but not exactly on the line to it, means that the flow has a high specific angular momentum about the hot companion. If a disk was not present before, a temporary disk may be formed. Such a disk may blow two jets for a short time. (2) Density variation along the jets' axes: If a disk was present with two jets, the enhanced accretion may lead to a denser jet. The consequence is two continuous jets, but with variation in density along the jet axis. (3) A tilted and precessing disk: The enhanced mass flux may be away from the equatorial plane. In such a case, the angular momentum accreted may have a direction tilted with respect to the permanent accretion disk. This may tilt the disk and cause a precession for a short time. This may be observed as precessing jets, but for a limited time.

Variation in the mass accretion rate may result from the pulsation of the giant as well, but to a lesser extent than I expect in a strongly magnetically active giant.

3.3. X-ray emission

Magnetically active MS stars have X-ray luminosity of up to $\sim 10^{30}$ erg s^{-1} (Stelzer & Neuhäuser 2001). The source of the X-ray luminosity is a hot corona and magnetic reconnection events, e.g., flares. Some observations indicate that cool giants may also emit in the X-ray band (Hünsch et al. 1998; Schröder, Hünsch & Schmitt 1998; Hünsch 2001), resulting most likely from magnetic activity. The presence of magnetic fields in AGB stars is inferred from maser polarization (e.g., Kemball & Diamond 1997). It seems that even a very slow rotation is enough to sustain a turbulent dynamo activity in AGB stars, i.e., an $\alpha^2\omega$ dynamo (Soker & Zoabi 2002). The fast rotating cool giants in SSs may be among the most magnetically active cool giants and those in which strong X-ray emission is expected. There is no basic dynamo theory to predict the level of magnetic activity in AGB stars; crude estimates for AGB stars rotating with periods of $\sim 10^2 - 10^3$ yr give $\dot{E}_B < 10^{30} - 10^{32}$ erg s^{-1} (Soker & Harpaz 1992). The temperature of the X-ray emitting plasma is most likely $T_x \sim 10^6$ K, as in MS stars. Magnetic flares may lead to detectable X-ray variability on time scales of weeks to months. I therefore speculate that the X-ray central source in the SS R Aquarii, with $L_x \simeq 4 \times 10^{28}$ erg s^{-1} and $T_x = 2 \times 10^6$ K (Kellogg et al. 2001) result from a magnetic activity on the surface of the Mira variable. X-ray observations of other SSs is highly encourage.

4. SUMMARY

The main goal of the present paper is to point out that the cool giant companion in most symbiotic binary systems (SSs) are likely to be strongly (relative to other cool giants) magnetically active.

The observational aspects of the magnetic activity are: (1) Imposing a global axisymmetrical mass loss geometry from the cool giant, i.e., a higher mass loss rate in the equatorial or polar directions. (2) Stochastic mass loss process, i.e., variation of mass loss rate with time and location on the giant's surface. The hot companion itself may cause a much larger departure from spherical symmetry in the circumbinary matter. Therefore, the asymmetry due to magnetic activity, both global and local, should be looked for near the giant's surface, e.g., SiO maser spots. The stochastic mass loss process may also cause variations in the intensity and direction of jets blown by an accreting companion. (3) As in main sequence stars, the magnetic activity may lead to X-ray emission. The expected temperature is $\sim 10^6$ K. The X-ray luminosity is hard to predict as there is no basic dynamo model for cool giants. A crude estimate is $L_x < 10^{30} - 10^{32}$ erg s^{-1}, in any case below the kinetic energy of the giant's wind. I suggest that this may contribute to the central X-ray source in R Aquarii, and hence I encourage more X-ray observations of SSs.

In arguing for magnetic activity of the cool giants of SSs, I assumed, based on the behavior of main sequence stars, that magnetic activity and X-ray luminosity increase with rotation velocity. I then showed that the cool companions in SSs are likely to rotate much faster than isolated, or in wide binary systems, cool giants, because of three processes: (1) In SSs in which the hot companion is a WD, the presently giant accreted mass from the wind of the WD's progenitor during the AGB phase of this progenitor. The accreted mass has a large specific angular momentum, hence it spins-up the MS progenitor. (2) The giant is spun up via tidal interaction with the hot companion. (3) Some fraction of the mass blown by the giant may flow back to the giant after acquiring angular momentum from the binary system, e.g., gravitational interaction with the companion.

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